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Navigating implementation dilemmas in technology-forcing policies: A comparative analysis of accelerated smart meter diffusion in the Netherlands, UK, Norway, and Portugal (2000-2019)

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ABSTRACT

This paper addresses the implementation of technology-forcing policies in open-ended diffusion processes that involve companies and regulators as well as consumers and civil society actors. Mobilising insights from the societal embedding of technology framework and policy steering theories, we investigate two implementation dilemmas that relate to an overarching tension between flexibility (to enable technological learning and stakeholder engagement) and coordinated push (to focus actors and drive deployment): a) early or late formulation of initial targets, and b) technocratic or emergent-adaptive implementation styles. We investigate these dilemmas with four comparative case studies of smart electricity meters between 2000 to 2019, which diffused rapidly in the Netherlands, Norway, and Portugal, but decelerated in the UK. We relate these differences to policy choices, and identify two patterns for successful implementation of technology-forcing policies: a) start with early targets and a technocratic style, but make adjustments if there are substantial protests or technical problems, and b) start with an emergent-adaptive style and formulate and enforce targets later, once technical and social stabilisation has occurred.

1. Introduction

Technology-forcing describes a regulatory strategy to accelerate the development and deployment of innovation by setting demanding performance standards or targets that are difficult to meet with existing technologies or implementation patterns. This strategy was relatively common to address environmental and societal problems in the 1960s and 1970s. Historical examples include the 1970 Clean Air Act, which articulated performance targets (90% reduction in hydrocarbon, carbon monoxide and nitrogen oxides emissions by 1975/76) that accelerated the introduction of advanced automotive emissions controls (Gerard and Lave, 2005; Lee et al., 2010); the 1971 New Source Performance Standards that accelerated the development and deployment of flue gas desulfurization systems (Taylor et al., 2005); and the 1966 Motor Vehicle Safety Act (NTMVSA), which pushed safety innovations including airbags into American cars (Gerard and Lave, 2007; Geels and Penna, 2015).

In these cases, the technologies to meet these performance targets did not exist (or only embryonically) when the targets were formulated. The cases were thus mostly about induced *innovation*. Once developed, diffusion of the new technologies was about requiring companies to install them in cars or power plants, which did not involve consumers.

The popularity of technology-forcing policies faded in the 1980s and 1990s, in part due to enthusiasm about liberalization and market-based policies and antipathies against governments 'picking winners'. Since then, increasing concern about climate change and other environmental problems has revived interest in technology-forcing policies. Examples include California's 1990 zero-emission vehicle (ZEV) mandate, which specified ZEV sales targets that accelerated the development of electric vehicles (Wesseling et al., 2015); Renewable Portfolio Standards, which

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many US states adopted in the 2000s to push utilities to produce a certain percentage of electricity from renewables by a specified date; the EU's 2003 Biofuels Directive, which specified increasing targets for biofuel mixing in automotive fuels (5.75% in 2010 and 10% in 2020); and the EU's 2010 Energy Performance of Buildings Directive, which set a target for all new buildings to be nearly zero-energy by 2020.

These more recent cases involve sales or deployment targets, indicating increased use of technology-forcing policies for accelerating the *diffusion* of existing but under-utilised technologies. The cases again focus on deployment by companies, except for the ZEV-case which also involved consumer adoption.

Extant scholarship conceptualises the *implementation* of technology-forcing policies as a contested process, involving struggles between policymakers and companies. On the one hand, policymakers push companies to accelerate the development or deployment of new technologies to address social or environmental problems. On the other hand, companies are reluctant because the new technologies add costs or lack consumer demand. Scholars have identified multiple factors that shape these implementation struggles, including the perceived credibility and capability of regulators to maintain and enforce targets (Gerard and Lave, 2005); tensions between regulatory stringency and uncertainty about technological feasibility (Lee et al., 2010); corporate resistance strategies such as litigation, lobbying or the exploitation of information advantages over policymakers (Wesseling et al., 2015; Taylor et al., 2005); and corporate compliance with targets (through increased R&D and deployment). Because implementation struggles unfold over multiple years, Gerard and Lave's (2007: 3) find that the effects of technology-forcing policies depend on "characteristics of the implementation *process*" (emphasis added).

We aim to make empirical and theoretical contributions to the technology-forcing literature. Empirically, we add a comparative case study of smart electricity meters which are a subset of advanced metering infrastructure to measure and analyse electricity usage and automate communication with energy suppliers. First discussed in the 1970s, smart meter debates gained momentum in the 1990s, when ICT-devices became more sophisticated and available. They became subjected to technology-forcing policies in the late 2000s. The 2006 European Union Energy End-Use Efficiency and Energy Services Directive (2006/32/EC) required member states to develop stronger demand-side policies, and Article 13 mentioned smart meters as an important element. A later Directive (2009/72/EC) articulated a specific target: if cost-benefit analyses (CBAs) of smart meters were positive, then member states were required to deploy them to at least 80% of consumers by 2020 or within eight years of such a CBA.

The smart meter case is also about accelerated diffusion, but it deviates from previous technology-forcing studies in several ways. First, the case involved not just policymakers and companies (who implemented the technology), but also millions of consumers (in whose homes smart meters were installed) and civil society actors (who shaped public debates and social acceptance). Second, companies mostly welcomed smart meters because of their problem-solving potential or envisaged cost savings (e.g. no more meter reader visits, fewer queries about estimated bills, simpler consumer switching). Third, smart meters are a more complex technology for incumbent companies than some previous cases (like power station scrubbers or catalytic converters in cars). One reason is that IT-hardware, software, and standards are particularly prone to unforeseen complications or incompatibility problems (Nightingale et al., 2003), which complicate implementation. Another reason is that the technical knowledge base of smart meters differs substantially from existing technical capabilities of energy companies, which complicates deployment.[1] Smart meters can also be configured in diverse ways, using various kinds and combinations of measurement devices, digital communications hubs, software programs, and wireless data transmission standards. They can also include or exclude In-Home Displays (IHD), which give consumers real-time information about domestic electricity use. Combined with the other two reasons, this means that identifying the best configuration of components is challenging.

Due to these differences, the implementation of technology-forcing policies for smart meters has particular complexities and dilemmas that we aim to address by making conceptual contributions. One complexity is that multiple stakeholders are involved, which not only increases policy complexity, but also poses challenges for implementation and engagement styles: while technocratic engagement with companies is difficult but (occasionally) accepted, the heavy-handed use of power and authority is even more difficult in policy engagement with consumers and civil society, and may generate social protest.

Another complexity is that smart meter technology had not yet stabilised at the time of the 2009 EU Directive. This created a policy dilemma for the timing of roll-out target setting, which could be formulated 'early' (i.e. before technical stabilisation) to articulate clear directionality (but with the risk of premature lock-in) or late (i.e. after technical stabilisation) to allow time for learning processes (but leading to a delayed start). Using insights from four policy steering theories, we will identify two options for each dilemma (technocratic or adaptive-emergent style; early or late timing of target-setting) that prioritise different relevant dimensions in the implementation of technology-forcing policies (enforcement, network governance, learning, and directionality).

Using four country cases, we will investigate how policy choices for these dilemmas influenced accelerated diffusion trajectories of smart meters between 2000 and 2019. The four selected countries are the Netherlands, United Kingdom, Norway[2] and Portugal. We chose a comparative research design because this is relatively novel in the technology-forcing literature (which mostly uses single cases), and because the four-country comparison enables empirical investigation of choices with regard to the two implementation dilemmas.

The article is structured as follows. Section 2 describes the conceptual framework. Section 3 discusses case selection and data collection. Section 4 presents the four country case studies. Section 5 makes a comparative analysis, and section 6 concludes.

2. Conceptual framework

To conceptualise the broader, multi-actor diffusion process that characterizes smart-meter deployment, we use the societal embedding framework (Rip and Kemp 1998; Deuten et al., 1997; Mylan et al., 2019; Kanger et al., 2019), which understands diffusion as a process of mutual alignment between a new technology and four environments (Fig. 1). While previous technology-forcing studies mostly focused on new technologies in business and policy environments, the societal embedding framework also acknowledges user and socio-cultural environments that were relevant for smart meter diffusion.[3]

Drawing on sociology of innovation and evolutionary economics, the societal embedding framework emphasizes mutual adjustments between

[1] This technical knowledge base difference was less pronounced for catalytic converters and scrubbers, which automakers and utilities were able to internalise through dedicated R&D programs and hiring policies (Taylor et al., 2005; Penna and Geels, 2012; Lee et al., 2010).

[2] Although Norway is not a member of the European Union, it often aims for close regulatory alignment to facilitate trade and other forms of exchange.

[3] Kanger et al. (2019) distinguish the transnational community of technical experts, who exchange experiences and discuss technical standards, as a fifth environment. We do not include this in our analysis for reasons of practical feasibility and to not overcomplicate our framework.

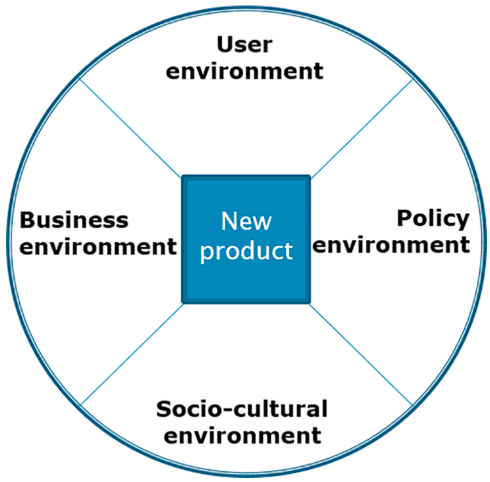

Fig. 1. Relevant environments for new products and practices (adapted from Deuten et al., 1997: 134)

new technologies and the four environments: "Technology adoption is an active process, with elements of innovation in itself. (…) Behaviours, organization and society have to re-arrange themselves to adopt, and adapt to, the novelty. Both the technology and social context change in a process that can be seen as co-evolution" (Rip and Kemp, 1998: 389). Combinations of the societal embedding framework and different policy steering theories (see Voß et al., 2007, for an insightful overview) are useful for better understanding the two implementation dilemmas for technology-forcing policies.

Timing of target-setting

With regard to technology, the societal embedding framework emphasises that adjustments are especially common in early developmental stages, called 'formative phase' (Bento and Wilson, 2016) or 'era of ferment' (Anderson and Tushman, 1990), when there are many technological uncertainties, multiple design variations, surprises and teething problems. Real-world experiments or demonstration projects are especially conducive in this phase to stimulate technological learning processes that may gradually reduce uncertainties and stabilise the technology (Hellsmark et al., 2016). The emergence of a dominant design then signals a shift to the 'growth phase' (Bento and Wilson, 2016) or 'era of incremental change' (Anderson and Tushman, 1990). Subsequent diffusion may still involve technological adjustments (Fleck, 1988), but these are usually smaller than in the formative phase.

These considerations sharpen the dilemma of the *timing* of target-setting. On the one hand, the basic motivation of technology-forcing policy is to set early demanding targets so that these accelerate the development and diffusion of new technologies. Policy theories such as new public management (Lane, 2000), mission-oriented innovation policy (Mazzucato, 2018) and the literature on promises, visions and goals (Van Lente, 1993; Sovacool, 2019) also suggest that policymakers can steer change processes by providing early directionality.

Possible advantages of *early* formulation of targets and technology specifications are signalling political leadership, creating clarity about the direction of travel, and accelerating change by convincing actors to mobilize resources and implement the technology (Van Lente, 1993). Potential risks and drawbacks of early target-setting are that this reduces the time for technological learning and adjustments, which are essential in early phases according to the societal embedding framework. Consequently, the early targets may later turn out to be unrealistic or contribute to sub-optimal technology specification and lock-in.

On the other hand, the societal embedding framework implies that it is safer to engage in *later* formulation of targets and specifications. This gives more time for real-world technological learning through pilots or demonstration projects (Hellsmark et al., 2016), which may lead to more informed target-setting and implementation choices. Policy learning theories, which address problems of complexity and knowledge uncertainties, also suggest that learning-by-doing should precede formal commitments. Lindblom's (1979) disjointed incrementalism approach, for instance, emphasises step-wise learning ('muddling through') and policy experiments to prepare the ground for later decisions. And the adaptive governance approach suggests that interventions in complex environments may have unforeseen consequences that require subsequent adjustments (Walters, 1986; Lee, 1999). Both of these policy theories would thus imply later target-setting in technology-forcing policies, once stabilisation has progressed. A potential drawback is that prolonged experimentation and deliberation may prolong uncertainty and delay full-scale commitment and diffusion.

There is no singular effective position in this dilemma. The literature offers successful examples of both early targets driving innovation and diffusion (e.g. the technology-forcing cases mentioned above) and of late targets being formulated as the diffusion process was unfolding, e.g. Austrian biomass district heating (Geels and Johnson, 2018) or the German energy transition (Geels et al., 2016).

Implementation style

With regard to stakeholders in the multiple environments, the societal embedding framework suggests that technology diffusion involves manifold activities and adjustment processes (which are discussed more deeply in Deuten et al., 1997; Mylan et al., 2019; Kanger et al., 2019). Companies may have to adjust production facilities, skills, or supply and distribution chains (Bolton and Hannon, 2016). Consumer activities may include purchase and adoption of the new technology, which are shaped by many factors including relative costs and performance, attitudes and perceptions (Rogers, 1996), and trust in the technology, suppliers and regulators (Mumford and Gray, 2010), which, in turn, are shaped by company reputations, people's views on policymakers, and media-reported consumer experiences. Public debates and NGO activities may further shape cultural meanings and social acceptance of new technologies (Hielscher and Sovacool, 2018; Roberts and Geels, 2018). Technological diffusion may also require new policies that influence the production or the use of new technologies, e.g. R&D subsidies, capital grants, safety regulations, reliability standards, adoption subsidies, or infrastructure investment programs (Brand et al., 2013).

Because many of these processes, particularly in the user and socio-cultural environments, are outside of policymakers' control, these considerations sharpen the dilemma of *implementation style* for technology-forcing policies. While top-down target-setting and enforcement (through warnings or penalties) may be feasible in interactions with firms, it is often less acceptable for policymakers (in democratic societies) to order consumers or civil society groups on what technology to adopt or accept. Top-down enforcement may be particularly challenging, or even exacerbate social acceptance problems (Scott, 1998), when consumers are less interested in the technology than policymakers anticipated or when public debates frame technologies negatively. Coalescing suggestions from innovation scholars (Garud and Karnøe; 2003; Sovacool, 2010; Hatanaka, 2020), we distinguish 'technocratic' and 'emergent-adaptive' implementation styles, which we will elaborate using policy steering theories.

A *technocratic* implementation style is characterized by centralized coordination, with a strong role for the state (and corporate lobbying) in selecting targets, specifying technological parameters, and driving deployment of the chosen technical design. Planning theories, which advocate this command-and-control style of steering, assume that policymakers have both sufficient expertise (to make correct analyses) and sufficient power or authority to enforce implementation (Friedmann, 1987; Cowley, 2015). While allowing for some (controlled) experimentation and (techno-economic) learning during the formative phase, this style approaches diffusion as a relatively straightforward process of deployment and delivery. One possible advantage is that authoritative decisions can create clarity and focus, which may help to coordinate and align efficient resource deployment (e.g. authority, money, technical competencies, organizational skills) by multiple actors. Another possible advantage is that the monitoring of implementation and the enforcement of compliance (through warnings or penalties) may accelerate diffusion.

But technocratic approaches also carry well-known risks (Scott, 1998; Voß et al, 2007). First, the focus on efficient techno-economic deployment may lead technocrats to ignore socio-cultural considerations and risks for particular social groups (Scott, 1998). Second, technocrats often engage in a narrow way with stakeholders (e.g. consumers, citizens, civil society groups), approaching them as 'obstacles' to be overcome (Devine-Wright, 2005) or as targets of information campaigns to be 'educated'. But if many stakeholders feel that their concerns are ignored, this interaction style may create alienation and social acceptance problems. Third, the presumption of superior knowledge may make technocrats reluctant to accommodate change during the deployment process, which is understood to be more about 'pushing' than about mutual adjustment. Although the technocratic style has acquired a bad reputation, and many case studies illustrate its failures (Scott, 1998; Garud and Karnøe, 2003), there are also examples of successful state-led planning and technology implementation (e.g. Turnheim and Geels, 2019; Lee et al., 2019; Mah, 2020).

The *emergent-adaptive* implementation style assumes that expertise and power are more distributed and therefore places greater emphasis on decentralised learning and stakeholder deliberation (with firms, citizens, or NGOs), which may lead to technological or policy adjustments (Voß et al., 2007). This style draws on network governance theories (Rhodes, 1997; Hendriks, 2008) which suggest that inclusion, consultation and interactive learning are more subtle way of achieving coordination. Distributed real-world initiatives and small on-the-ground projects may act as vehicles for interactive learning, while public hearings and consultations can stimulate the voicing of experiences and concerns. The resulting lessons and insights may then lead to adjustments that inform subsequent larger projects, making the overall implementation processes more adaptive and flexible (Garud and Karnøe, 2003; Geels and Raven, 2006).

The emergent-adaptive style also has potential drawbacks. First, multiple distributed projects and initiatives may lead to fragmentation, especially if interactive learning is limited and actors do not exchange information (Turnheim et al., 2018). Second, learning and stakeholder engagement take time and may delay formal policy commitment and initial diffusion (Ciplet and Harrison, 2020).

Since both implementation styles have advantages and drawbacks, we do not privilege one style over the other. Rather, we propose that both styles are extremes, and that countries may use a mix of styles and combine elements of both in actual implementation programs. Our comparative smart meter case study empirically investigates what (mix of) implementation styles different countries adopted and how this influenced diffusion trajectories.

Table 1 summarises the advantages and potential drawbacks of the different choices for the two implementation dilemmas. The analysis in section 5 will indicate how these played out in the different country-cases.

Table 1
Summary of implementation dilemmas in technology-forcing policies

	Advantages or benefits	Risks or drawbacks
Early formulation of targets and technology specifications	- Creates clarity about direction of travel; - Stimulates early commitments and resource allocation; - Signals political leadership.	- Unrealistic targets that prove difficult to meet, leading to postponement and/or impression of failure; - Early technology specifications may turn out to be wrong.
Late formulation of targets and technology specifications	- Creates more time for learning and adjustments, leading to more informed later targets and specifications.	- Late formal targets may create uncertainty, delay commitments and slow diffusion.
Technocratic implementation style	- Authoritative decisions may create focus and coordinate resource deployment; - Monitoring of implementation and enforcement may accelerate diffusion.	- Limited and narrow stakeholder engagement may create social acceptance problems; - Ignores broader considerations - Exhibits reluctance to make adjustments.
Emergent-adaptive implementation style	- Decentralized projects allow for interactive learning and mutual adjustments; - Learning and stakeholder engagement make implementation more adaptive and flexible.	- Diffusion may be slowed by fragmentation and limited exchange between projects; - Slow initial diffusion because of time-consuming articulation processes and delayed formal commitment.

3. Research design and methodology

3.1. Case selection

To investigate the relationship between technology-forcing policies and accelerated diffusion of smart meters, our comparative case study design focuses on four countries: the United Kingdom, Norway, Portugal and the Netherlands. Several considerations informed the selection of these countries. First, we wanted to investigate countries that an early overview of the European Smart Metering Landscape identified as 'dynamic movers' (see Fig. 2), which means they had (at that time) a clear roll-out path due to specified targets and/or engagement in major pilot projects. From this group, we excluded Sweden, Italy, Finland and Malta, because these countries started roll-out programs before the 2009 EU Directive (for country-specific reasons such as reducing electricity theft in Italy) and because they used simpler, early-generation smart meters.

Second, from the remaining set, we chose two countries that attempted early target-setting and two countries with late targets. Using the benefit of hindsight, we also compared realised diffusion trajectories (see Fig. 3) with the targets, to select countries that looked particularly interesting or puzzling to us. The following arguments underpinned our selection:

- The UK set targets early (in 2009), committing the country to 100% roll-out by 2020. Despite substantial initial preparation, diffusion proceeded slower than anticipated (with electricity smart meters reaching only 9.8 million homes in 2019 out of a total of 27.8 million homes), leading the government to postpone the deadline to 2024.
- The Dutch government attempted to set early targets (in 2008), but these encountered societal opposition over privacy concerns, which delayed acceptance until 2011. While this led Zhou and Brown (2017: 26) to characterize the Dutch case as "slow policy adoption and technology implementation", Fig. 3 shows that diffusion accelerated in recent years, placing the country on track to meet its 2020 targets.
- Norway was late in establishing its smart meter program, but met this target through very rapid diffusion during 2017 and 2018.
- Portugal arrived late (in 2015) at a positive cost-benefit analysis, but did not follow this up with an official target. Instead, smart meter roll-out was stimulated through large-scale projects and implementation incentives, which succeeded in accelerating diffusion.

As the brief summaries indicate, these four countries show interesting similarities and contrasts in diffusion speed and trajectory, which we aim to describe and explain by investigating mutual adjustments between smart meter technologies and the four environments and associated social groups.

Our research design and case selection arguments imply that we treat the countries as four independent cases in which national contexts and

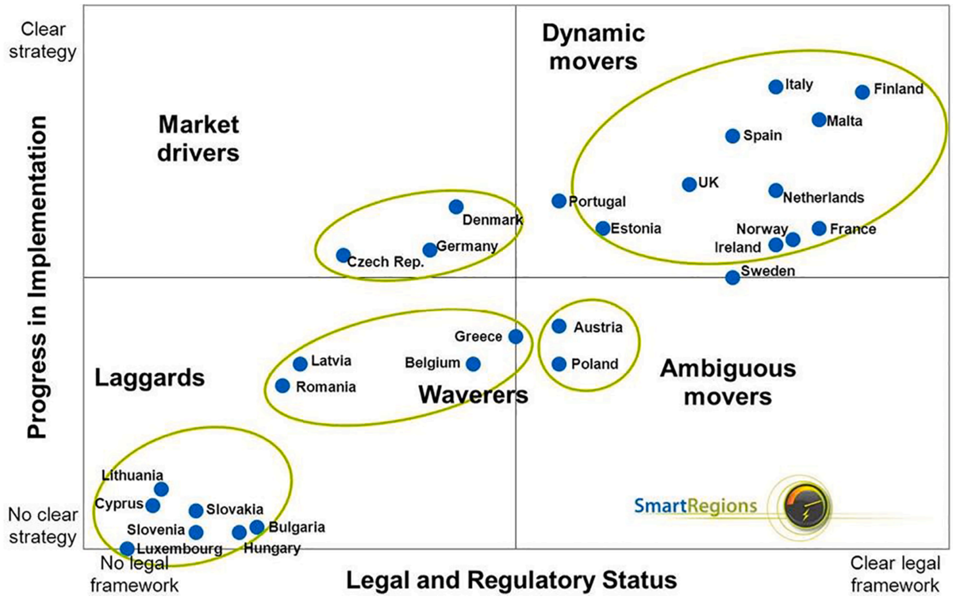

Fig. 2. Mapping smart meter programs in European countries (Smart Regions, 2012: 19)

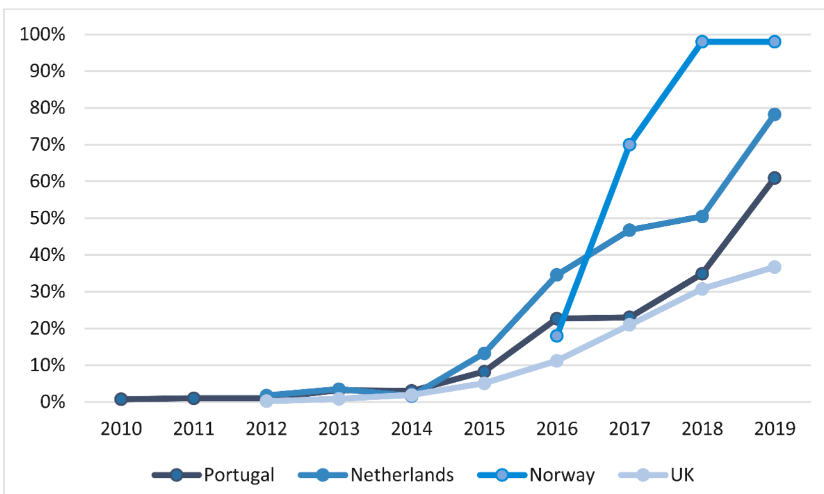

Fig. 3. Smart meter diffusion trajectories four countries (constructed using the best data available for each year from the UK Department of Business, Energy and Industrial Strategy, Netbeheer Nederland, Norwegian Water Resources and Energy Directorate, and Portuguese Energy Services Regulatory Authority)

interactions between domestic groups (firms, policymakers, consumers, civil society groups) are likely to be most important in shaping diffusion trajectories. We acknowledge that transnational influences may play some role, but do not consider these in the analysis.

3.2. Data-collection and analysis

Since the smart meter roll-out remains a recent and ongoing process, reporting has not fully stabilized. This posed challenges for data-collection, especially for the Portugal case, where the lack of formal government targets means there is limited official reporting and thus scarce data. We therefore used multiple data sources, including academic publications (which are abundant for the UK and the Netherlands, sufficient for Norway and relatively sparse for Portugal), government publications (e.g. White Papers, cost-benefit assessments, progress updates by regulators or other official bodies including dedicated webpages), reports by corporate organisations involved in roll-out programs (e.g. Smart Energy GB; Netbeheer Nederland; Energy Norway; Energias de Portugal), newspaper articles, reports and commentaries by wider stakeholders (e.g. Consumers' Association; National Audit Office; Institute of Directors; Energy Research Centre of the Netherlands). Additionally, some of the authors have in-depth knowledge of three of our four countries through their involvement in previous smart meter research projects that used primary data-collection methods, including a UK media discourse analysis in 2017, followed by 16 expert interviews and a UK focus group in 2018, living lab analysis (including interviews and focus groups) of 46 Norwegian households, and 80 Portuguese energy sector interviews, investigating solar energy and smart meter uptake.

This diversity of data-sources enabled us to find information for all the conceptual categories from the societal embedding framework, and also afforded a greater degree of potential triangulation. The first step in the research process was to construct concise first-round descriptions of how smart-meter diffusion trajectories unfolded in the four countries, triangulating the different data-sources and organizing them along the conceptual categories. In a second step, we compared the four cases and reflected on similarities and differences in outcomes and diffusion trajectories. We had several rounds of discussion, trying out different analytical schemes to interpret the data, until we settled on a focus on implementation styles and the timing of formulating initial targets and roll-out specifications. In a third step, we adjusted the case-descriptions to better highlight these issues, and prepared the ground for the structured analytical comparison in the fourth step, which further articulated different patterns in the cases. So, although the article follows the normal linear and logical writing format, the actual research process involved iterations and interactions between theory and data (Alford, 1998; Van Maanen et al., 2007).

The case descriptions in the next section are brief due to space constraints and focus on the main developments. This means that it was, unfortunately, not possible to address all details and intricacies, though we do cite more detailed extant thematic literature. To capture temporal patterns, each case is divided into three periods, which discuss the initial drive for smart meters, subsequent preparation, and mass-roll-out. For each period, we describe the main developments in technology and the four environments from the societal embedding framework. Descriptions of some environments are brief or absent when little happened in a particular period. Section 5 makes a comparative analysis of the four cases, using the conceptual framework.

4. Results: Four diverging smart meters case studies

4.1. The Netherlands

4.1.1. Top-down government planning (2005-2008)

Business environment: Following electricity market liberalization in 2004, smart meters were first proposed as part of meter market restructuring for households and small businesses (Cuijpers and Koops, 2013). The eight Dutch Distributed System Operators (DSOs) were also interested in smart meters as tools to improve operational efficiency and correct administrative problems with billing.

Policy environment: Policymakers perceived smart meters as a way of facilitating more energy market competition (easy switch for consumer) and stimulating behaviour change and energy savings (European Commission, 2011). A 2005 Cost Benefit Analysis (CBA) suggested a positive business case of approximately 1.3 billion euros (SenterNovem, 2005). Policy debates gained momentum with the 2006 EU Directive, which the Dutch government interpreted as a justification for the introduction of smart meters. It was also expected that the roll-out of smart metering would stimulate the introduction of prepayment and flexible tariff schemes (Hoenkamp et al., 2011).

In 2008, the government put forward a Smart Meter Bill, which proposed a 100% roll-out that would be mandatory, backed up by hefty fines or imprisonment for people refusing one (Hoenkamp et al., 2011). The proposed technical specifications meters would also include in-home displays; an alarm for unexpected peak usage; real-time measuring; possibilities for remote programming of appliances; and possibilities for communication with other meters.

4.1.2. Public protests and policy adjustments (2008-2013)

Civil society: The government's proposal encountered heated public protests in 2008-2009, which led to a switch from a top-down to a more collaborative policy approach (Cuijpers and Koops, 2013). Foremost were the issues of privacy and public distrust, which centred on anxieties of smart meters as representing a 'spy in the home' (Naus et al., 2015). The Consumers' Association published a report in 2008, which claimed that a mandatory roll-out of the meters would constitute an infringement of the right to privacy (Hoenkamp et al., 2011). This violation was due to the automatic remote reading of energy use every fifteen minutes, as specified by the National Technical Agreement (NTA) 8130 Bill. The Dutch Applied Research Institute also published a report criticizing the smart meter's NTA 8130 standard. They argued that the meter did not provide a solution for sustainability or energy efficiency as the display was not different from the old meter and thus would not influence consumer's energy awareness (KEMA, 2012). As public debates became widespread, concerns were also taken up by the Committee for the Protection of Personal Data, which advised against the smart meter NTA due to its inconsistency with the Personal Data Protection Act (KEMA, 2012).

Policy environment: Responding to these public concerns, the Dutch Senate rejected the government proposal in 2009. The subsequent political debates resulted in a revised legal framework in 2010, which stipulated that the roll-out would be voluntary with various options for consumers who could: a) keep the traditional meter, b) have a smart meter where no data is transmitted automatically, or c) limit automatic data transmission to bi-monthly reading, annual billing, supplier changes and relocation (KEMA, 2012).

Technology: The legal changes also implied changes in technical specifications so that Dutch smart meters would not satisfy three functions that meters in many other countries would: a) advanced tariff systems, b) remote ON/OFF control of the supply, and c) fraud prevention and detection (European Commission, 2019). But the smart meters would still allow the following functionalities: allow remote reading by the operator, provide two-way communication for maintenance and control, provide readings directly to consumer and/or any third party, upgrade readings frequently enough to enable energy saving schemes, and provide secure data communications.

Because the smart meter programme had changed substantially, a second CBA was conducted in 2010 (KEMA, 2012), which concluded there was still a positive business case of around 770 million euro, despite more limited functionality (European Commission, 2019). The largest benefits were estimated to come from reduced energy consumption (assumed to be 3-6% for electricity), increased (retail) competition, consumer management and reduced meter reading costs (KEMA, 2012).

User environment. Once the revised Smart Meter Bill came into force in 2012, policymakers and businesses commenced broader public engagement activities and pilot schemes to sensitize consumers and gain information about consumer preferences and market options. One pilot project testing dynamic pricing models, which was called "Your Energy Moment", was conducted between 2012-2015 to gain experience with technical, economic and social options to create flexibility and increase sustainability in the energy consumption of consumers (Naber et al., 2017). These kinds of activities represented a new kind of engagement with both users and broader societal debates.

Business environment: DSOs also started a trial period of installation in 2012, during which they deployed 600,000 smart meters "to gain experience and signal possible problems at an early stage, in order to take additional measures in time for the second phase, the large-scale roll-out" (Dutch Government 2014). The Authority for Consumers & Markets and the Netherlands Enterprise Agency further investigated roll-out strategies, customer satisfaction and energy savings. The DSOs also joined forces in a 'Smart Buying' project (Landis and Gyr, 2014).

Policy environment: An evaluation in 2014 found that the pilots had been successful and that the roll-out could be expanded (Netherlands Government, 2014). Concurrently, a large-scale smart meter feedback research programme, known as 'Smart Metering Activation and Response Trials', was carried out, which measured quantitative consumption changes in energy use. The study found that households with a smart meter and bi-monthly home energy reports used only 0.6% less electricity, compared to the control group, which was a lot less than the 3-6% reduction which underpinned the cost-benefit analysis (Netherlands Government, 2014).

4.1.3. Large-scale implementation and new wave of explorations (2014-2019)

Business environment: The mass roll-out started in 2014, with more than 1 million installations in that year (European Commission, 2019). The installations occurred region by region and continued relatively smoothly through to 2019, by which time diffusion had reached 78%. The roll-out was led by the DSOs whose activities were coordinated by

Netbeheer Nederland (Network Management Netherlands). The mass roll-out was also increasingly facilitated by advances in smart management, and some DSOs (such as Enexis) worked with American platform developer Cisco Jasper to develop an online control centre that would automatically identify technical problems with the smart meters (Power Technology, 2018).

User environment: Home installation was free of charge, but, as DSOs would have to recoup costs of the meter and installation, consumers would ultimately pay through their bills. In-home displays were optional, but customers had to pay extra for them. Although voluntary, the roll-out was a mix between corporate initiative and consumer response. Concretely, DSOs sent a letter to households, announcing that a smart meter would be installed in their home at a certain date (https://www.netbeheernederland.nl/). Consumers could refuse at no cost (or opt for particular smart meter settings that addressed their privacy concerns). But if they later changed their mind and wanted a smart meter, they had to pay a fee (€72.60). The roll-out thus had an 'opt out' design, whereby it was assumed that consumers were happy to have a smart meter, unless they actively refused.

Technology: The mass roll-out was accompanied by new innovations and business models, particularly around the promise of 5G and the Internet-of-Things. Smart meters were increasingly seen as "an essential part of the smart grid" (Power Technology, 2018). Despite relatively smooth progress, new technical problems appeared during the roll-out, particularly with regard to meter inaccuracies and ineffectiveness. Some smart electricity meters reportedly gave readings that were higher than they should be (Power Engineering, 2017). The problems were linked to the design of the meters and how they were unable to accurately measure usage with energy efficient devices and modern switches such as dimmers.

Civil society and user environment: The technical problems were widely reported in the media and led to an increase in meter refusals by households, which by the end of 2018 had reached 11%, while 2% had asked to deactivate the communication function (European Commission, 2019). Technical innovations also led to new consumer products and business models, which often related to smart phones. About 18% of consumers with a smart meter also adopted an 'energy consumption manager', such as a smart thermostat, which offers direct feedback to allow energy consumption reductions (European Commission, 2019).

4.2. United Kingdom

4.2.1. Top-down government initialization and planning (2005-2009)

Policy environment: Wanting to act on climate change, the Labour government's interest in smart meters was triggered by a study that suggested that they could lead to energy savings between 5% and 15% through information 'feedback' on energy use (Darby, 2006). Smart meters were thus seen as a tool for empowering consumers to save energy while also enabling the grid to manage increasing amounts of intermittent renewables (Xenias et al., 2015). The 2006 EU Directive further stimulated the government to start debating which "forms of metering, tariffing and billing are feasible" (Darby, 2008: 70). In 2008, the government announced its decision to provide smart meters to all households by 2020 (Sovacool et al., 2017). The 2009 impact assessment of the Smart Meter Implementation Programme (SMIP) suggested that the implementation of 53 million residential and non-domestic gas and electricity meters by 2020 would cost about £8.1 billion. The government also decided to make energy suppliers responsible for the roll-out and ruled that they would bear the up-front costs, which they could subsequently recover through consumer energy bills (Sovacool et al., 2017). The suppliers were considered to be well placed to do this due to their long-standing experience of dealing with customers and their more dynamic reputation compared to DSOs (Bolton and Foxon, 2015).

Technology: The government's 2008 decision stipulated that smart meters should include in-home display (IHD) units. This technical specification decision was made before the results of smart meter pilots, such as the Energy Demand Research Project (EDRP) from 2007 to 2010, were collated and analysed (Darby, 2009).

Business environment: The energy supply companies were willing to be involved in the smart meter roll-out, because their involvement in the EDRP-pilots had provided them with positive results (Darby et al., 2015). The government's CBA also suggested that smart meters would have large supply-side benefits and cost savings, e.g. removing the need for meter reading site visits, reduced consumer queries and call centre traffic about estimated bills, cheaper consumer switching, and enhanced grid management. The energy companies did, however, argue against the inclusion of IHDs (which added costs and complicated installation), but the government rejected this.

Consumers and civil society: The SMIP's steering committee comprised DECC officials and industry actors, but no consumer or civil society organisations, whose involvement was thus minimal (Sovacool et al., 2017). Design specifications and legislation were also "developed in a largely top-down industry-led process with little input from, or attention to, the householder" (Pullinger et al., 2014: 1158).

4.2.2. Protests, hiccups, and superficial attention to complaints (2010-2015)

Policy environment: During the preparation stage, parliamentary committee enquiries raised major concerns (NAO, 2014; PAC, 2012). In addition to rising cost estimations, the rapid pace of technological change, data security, and implementation efficiency, the enquiries pointed to continuing uncertainties over how customers might gain from the roll-out. In response, the government published successive CBAs, which suggested that rising costs would be offset by rising benefits (see Table 2), leading to increasingly positive estimates of net present value. The 2014 CBA suggested that consumers and energy companies would enjoy the largest benefits (Fig. 4).

Observing Dutch social acceptance problems with mandatory roll-out, UK policymakers announced in 2012 that their smart meter roll-out would be voluntary, based on an 'opt-in' model, in which consumers had to ask energy companies for a smart meter (Orlowski and Bray, 2012).

Technology: Early implementations showed that smart meters did not work well in high-rise flats, basements and rural areas (Sovacool et al., 2017). Indeed, by early 2015, 134,000 of the 1.3 million new "smart" meters installed only functioned as traditional meters, requiring manual readings due to technical limitations (Gosden, 2015). A further problem was that first-generation ('SMETS1') meters were incompatible with some suppliers, which complicated consumer switching.

Civil society: Negative media discourses started to coalesce around three main issues: technical functionality, costs, and privacy (Hielscher and Sovacool, 2018). Problems with technical functionality in certain settings were widely covered. In 2015, OVO Energy and EDF reported that 6% of their installed meters were experiencing billing problems and 0.5% were experiencing technical glitches (Palmer, 2015). This led to media reports about hundreds of thousands of households potentially being "trapped" with malfunctioning meters and a large backlog of customer complaints (Shannon, 2015). Although it was expected that future software upgrades could convert SMETS1 meters to SMETS2 meters, these problems tarnished SMIP's public reputation and also left

Table 2
Successive cost-benefit estimates of smart meter introduction programme (data collected from successive government impact assessments)

Year	Costs (£billion)	Benefits (£billion)	Net Present Value (£billion)
2009	8,110	11,700	3,590
2010	9,119	14,154	5,035
2011	10,757	15,827	5,070
2012	10,850	15,689	4,839
2013	12,114	18,774	6,660
2014	10,927	17,141	6,214

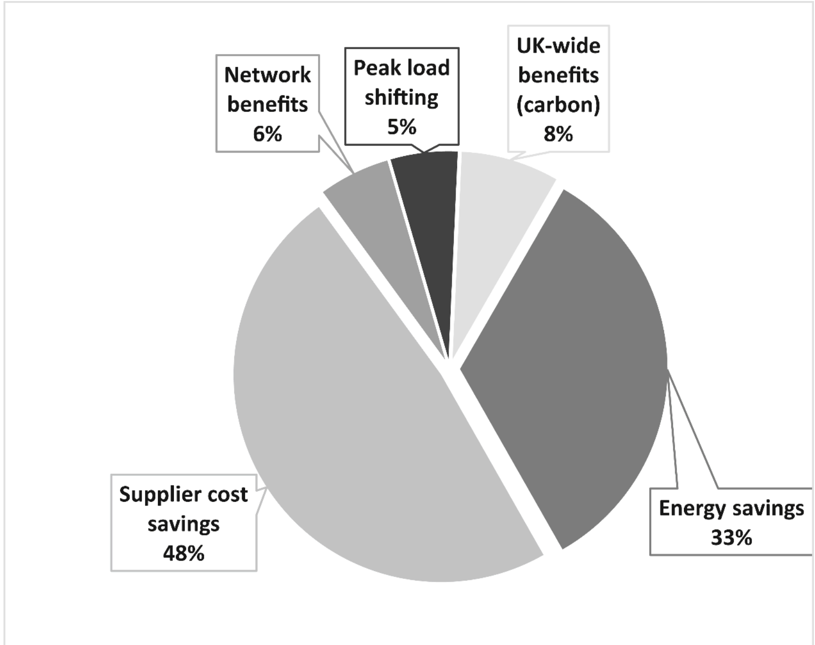

Fig. 4. High-level overview of benefits of the UK smart meter program (Author's modification of DECC, 2014: 15), total amount is £17.141 billion)

roughly 12.5 million SMETS1 meters vulnerable to running in 'dumb mode' (NAO 2018).

Despite the government's successive cost-benefit analyses, public debates also continued to express concern about rising costs. In 2015, the Institute of Directors published a critical report (IoD, 2015) warning that SMIP could become the government's next IT disaster. Estimated annual household benefits were also lowered over the years, from £200 per year in initial estimates to £46 per year in 2013 to £11 per year in 2016 estimates (BEIS, 2016). Public debates thus increasingly questioned the underlying 'business case'.

Privacy was also discussed, with libertarian and conservative media warning that the government could use smart meters to increase its control and surveillance over citizens. Other concerns were that hackers and cyber-terrorists could break into the system to disrupt the grid or carry out theft or fraud by intercepting bills and private data (Sovacool et al., 2017). These stories, amplified by groups such as *Stop Smart Meters!*, sowed doubts among the public about the safety and security of smart meters and hindered the roll-out (Sovacool et al., 2019).

These various debates generated substantial scepticism around smart meters, which successive UK governments have struggled to overcome (Hielscher and Sovacool, 2018). In turn, this scepticism led to delays and spiralling programme costs, appearing to confirm public doubts. Substantively, the start of the large-scale roll-out was delayed from 2014 to 2016.

Business environment: Evaluations of pilot studies suggested that energy savings from information 'feedback' might be more limited than was initially assumed, with estimated energy savings reduced from 5-15% to 1-3% (Shipworth et al., 2019). Companies also reported that the IHDs being used in SMIP had a problem of time-delay in showing real-time prices and then in translating these data into demand reductions. These IHD problems led companies to question SMIP's technology choices, arguing instead for cheaper apps that would allow phones, tablets, or personal computers to capture meter readings with no additional hardware cost (IoD, 2015). However, by this stage, SMIP-officials were committed to a standardized roll-out of IHDs, and reluctant to consider changes.

Although the 'Big Six' energy companies (EDF, E.ON, SSE, British Gas, Scottish Power, N-Power) dominated energy provision in the previous period, increased consumer switching in the 2010s attracted more new entrants, which exacerbated competition as they took markets shares from the incumbents (Fig. 5).

The logistics of the supplier-led roll-out and the fragmented nature of energy markets (with 72 competing energy suppliers in the period 2010-2015) created extra costs and delays (Sovacool et al., 2017): since different households in a street bought their electricity from different suppliers, installation could not be done on a standardized, street-by-street basis but had to be done through individual site visits. Limited public trust in energy suppliers further undermined the roll-out, with growing concerns since 2016 about the health impacts of smart meters (Hielscher and Sovacool, 2018).

Policy environment: To alleviate public concerns and generate interest in the smart meter roll-out, the government created the Smart Meter Central Delivery Body in 2013, along with a new marketing campaign led by a new organisation, Smart Energy GB. Their campaigns featured advertisements with personified units of gas and electricity ("Gaz" and "Leccy"), which were disseminated via television, print, and email (Sovacool et al., 2017).

In response to concerns about limited consultation about issues such as fuel poverty and vulnerabilities (particularly focusing on the elderly and digital exclusion), the government also strengthened its engagement with civil society organizations, such as Consumer Futures, Fuel Poverty Advisory Group, and Age UK. These organizations shared their experiences and insights that could feed into the large-scale roll-out (NAO, 2018).

Following the consultations, the government also introduced the requirement that suppliers/installers demonstrate the smart meter to consumers and offer energy savings advice during the physical installation (BEIS, 2018). Energy companies disliked this requirement, because it raised costs and slowed installation. But the government persisted because the face-to-face interaction during installation was deemed essential in securing the potential gains from energy consumption through behaviour change (BEIS, 2018). Subsequent implementation of this requirement has been mixed, because energy advice was often given in a rushed and routinized way to satisfy targets.

4.2.3. *Stilted progress and lingering doubts (2016-2019)*

Business environment: The large-scale roll-out commenced in 2016, but installation failures remained commonplace, with more than 10% of

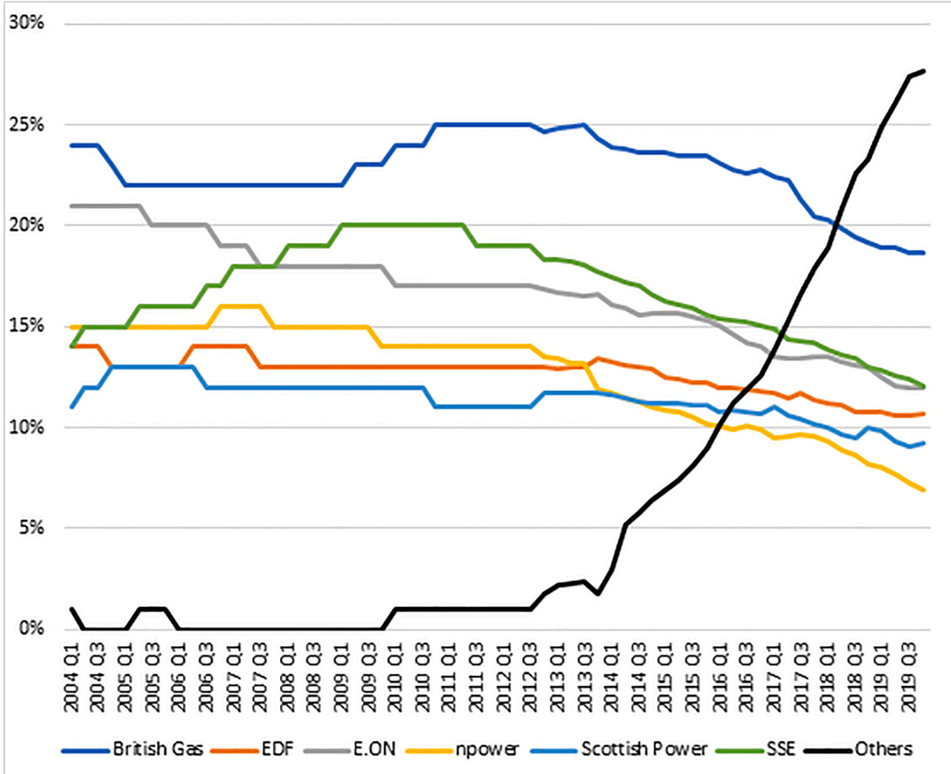

Fig. 5. UK market share evolution of energy companies, 2004-2019 (Ofgem, 2020: 1)

homes requiring multiple visits to complete the installation (Utility Week, 2017). Reasons for these failures ranged from customers not being present and installations taking longer than expected, to meters not being accessible, or to difficulties with multiple occupancy properties. After two relatively successful years, quarterly installation rates decreased in 2018 and 2019 (Fig. 6).

Policy environment: The government's own policies further complicated the roll-out. Indeed, despite knowing that SMETS1 meters had problems, the government continued to force suppliers to install these meters in view of the looming 2020 target. It did this simply "because the Department [BEIS] wanted to speed up the program" (NAO, 2018).

Civil society: The problems with functionalities and SMETS1 standards, combined with years of negative debates, tarnished the public reputation of smart meters. Initial concerns about privacy and surveillance were joined by new concerns over possible health impacts of smart infrastructures and more practical concerns with cost and effectiveness (Hielscher and Sovacool, 2018). The (un)reliability of energy companies and home installation problems also became issues of public debate (Connor et al., 2018).

User environment: Although the first SMETS2 meters began to be installed in 2017, public trust remained problematic (Meadows, 2018), which resulted in lukewarm consumer interest. BEIS's (2018b) own consumer surveys revealed that one-in-ten (11%) were not satisfied with their smart meter installation. Only 82% of attempted installations were completed on the first attempt and a further 5% were completed at a later date (BEIS, 2019b). Less than half of visits resulted in advice on how to save energy with their smart meters, and some households also experienced increased stress levels because their in-home display made them more anxious about the costs of energy use (Hodges et al., 2018). In 2019, only 39% of non-owners said they would seek or accept a smart meter within the next six months (Smart Energy GB, 2019).

Policy environment: Because of the multitude of problems and slow progress, the Conservative government announced in 2019 that it would delay the roll-out deadline from 2020 to 2024. Although the delay is expected to increase total programme costs to over £13.5bn, the government stated that it would allow for a greater focus on consumers (BBC, 2019). The delay arguably also represented an accommodation of the interests of energy suppliers who were racking up fines for slow delivery (Ofgem, 2018). It also, however, reflected the views of organizations such as the Citizen's Advice Bureau who had emphasized the need to focus on quality and customer care over speed.

4.3. Norway

4.3.1. Business push for smart meters (2000-2007)

Business environment: The push for smart meters came from Norwegian grid utilities, which saw it as a way to deal with the variability in hydropower (which generates about 95% of electricity in Norway, with another 3% from wind power), due to year-to-year differences in precipitation, which create variation in power prices (Ministry of Petroleum and Energy 2016). Already in the mid-1990s, there were discussions among the 140 DSOs, which have regional grid monopolies, about smart meter potential for remote control of electricity use. Some DSOs engaged in pilot projects in the late-1990s, but these showed that smart meters were not economically feasible (Inderberg, 2015).

In 2001, however, low precipitation levels and high electricity price volatility stimulated renewed interest from smaller, regional DSOs, who engaged in further pilots. Encouraging results, and Italy's decision to roll-out smart meters during 2002-2005, stimulated further engagement with smart meters from the industry association *Energy Norway* (Inderberg, 2015). The Norwegian telecom-sector (particularly Telenor) also became interested in smart meters, which led to further technical development and pilot projects. These deepened the understanding of smart meters and broadened views on potential benefits to include peak shaving, grid coordination, operational benefits and consumer benefits (e.g., efficient billing, energy savings, energy security). In 2006, *Energy Norway* commissioned a report suggesting that consumer and societal

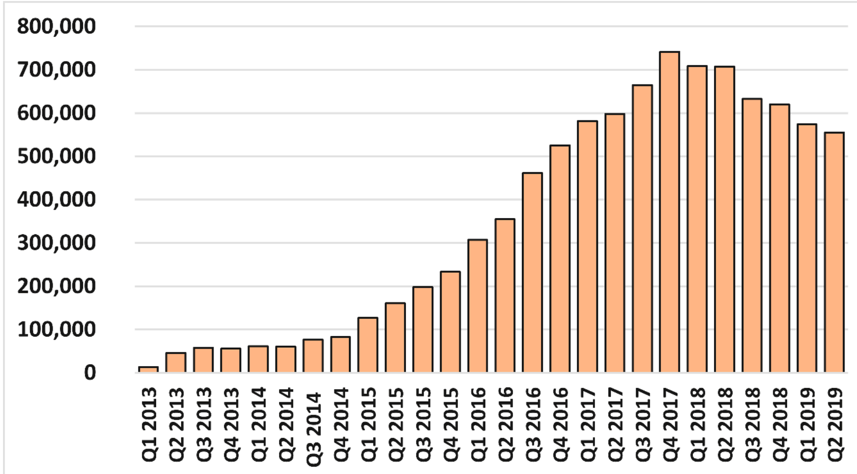

Fig. 6. Quarterly installation of smart meters by large suppliers in Great Britain, 2013-2019 (data from BEIS, 2019a)

benefits would be substantial (ECGroup, 2006).

Policy environment: The government initially had a 'hands-off' attitude towards smart meters (Inderberg, 2015). But increasing interest from DSOs and telecom companies stimulated debates within the national regulator Norwegian Water Resources and Energy Directorate (NVE) (Ballo, 2015). In 2006, NVE published a report that was inconclusive about the economic feasibility of smart meters, due to high regional variations (Inderberg, 2015). But because 2006 was a very dry year that led to heated media debates about fluctuating electricity prices, the Ministry of Petroleum and Energy demanded further engagement from NVE (Inderberg, 2015). Stimulated by business, media and political pressure, NVE signalled in 2007 that it intended to develop smart meter regulations aimed at a possible smart meter roll-out (Inderberg, 2015).

4.3.2. *Policy and business orchestration to prepare mass roll-out (2008-2015)*

Policy environment: To prepare more specific regulations and design characteristics of a possible smart meter roll-out, the regulator NVE held four public hearings – in 2008, 2009, 2011 and 2013, open to inputs from all stakeholders. Business organisations were crucial participants, because NVE "recognized that expertise on smart meters, a new field for regulatory practices, was to be found largely with the interest organizations, research institutions and DSOs" (Inderberg, 2015: 101-102). The first public hearing discussed new metering regulations including remote control by DSOs. At the time, NVE estimated that about a dozen of Norway's 140 DSOs had implemented smart meters, that most of these were small with less than 15,000 users each, and tentatively targeted 2013 for a smart meter roll-out (NVE, 2008).

The 2009 public hearing focused on implementation feasibility, which led to a decision to delay the roll-out from 2013 to 2014, while major players advocated further delay to early 2017. Other discussion items were prosumer interests, data protection, and the 80% roll-out requirement by 2020 of the 2009 EU Directive (Inderberg 2015). During the 2011 hearing, smart meters received high political attention, due to the dry and cold winter of 2010, which create high electricity price volatility. This led to the smart meter regulation that approved a mandatory roll-out of over 2.5 million smart meters by DSOs by 2017. Two years later, in 2013, however, the roll-out deadline was suddenly pushed back to 2019 for "unclear political reasons" (Inderberg, 2015:103). Although a 2015 cost-benefit analysis was negative, the roll-out target was maintained because sectoral actors argued that smart meters would have benefits that were difficult to foresee and quantify (Ballo, 2015).

Technology: The public hearings and on-the-ground projects led to various adjustments in technical specifications. The in-home display and remote steering options were both dropped after the 2009 hearings (Inderberg 2015), while the 2011 hearing led to inclusion of an open communication channel accessible to third parties.

Business environment: Industry players were keenly involved in debates about design specifics of the roll-out program and interacted closely with NVE. This led to the early identification of streamlining roll-out needs such as standardisation which, while not mandatory, was regarded as desirable by *Energy Norway*, given the large number of DSOs in a small market. It was also decided that smart meter investment costs would be paid by DSOs, who would recover these in small annual chunks through grid access charges (Ballo, 2015). And it was decided that the roll-out would be mandatory with limited opt-out options and stiff penalties (which could exceed €200).

While some DSOs had started the roll-out by 2013, most smart meters installations were planned for 2017 and 2018 (Alskaif and van Sark, 2016). This provided extra time for pilot programs, which multiplied, as DSOs were keen to test communication infrastructures, data management programs, and various feedback solutions.

Wider publics: While parliamentary committee and public hearings brought discussions into the wider public sphere, societal debates were characterized by limited concern. One reason for this de-politicisation is that smart metering was not framed and understood as a transformative technology but as a technical upgrade of the electricity grid representing the 'next natural step' (Inderberg, 2015: 98). This was also visible in the technical design choices (which excluded IHDs and remote control). Another reason is that Norway is characterized by relatively high levels of trust in public institutions, which led most people to regard the smart meter roll-out as properly considered by NVE and the Ministry. Even the investment of 10 billion kroner (approximately €1 billion), which represented significant uncertainties, and gradual recovery of over €300 per consumer, did not trigger much societal debate.

User environment: Although consumer organisations were formally consulted during the public hearings, their influence was relatively limited because they were not well integrated into the NVE policy streams (Inderberg, 2015). During the 2009 public hearing, the idea of in-home displays was dropped, despite some advocacy by consumer organisations. The rationale was that Norwegian consumers were not very concerned about reducing electricity use, because they viewed hydro-power as renewable. Instead of IHDs, it was decided that smart meters should have an open communication channel for third-party interfaces, which would enable consumers to access consumption data if they wanted.

4.3.3. Rapid roll-out and smart meter installation (2016-2019)

Policy environment: The Ministry of Petroleum and Energy left oversight and control of the mass roll-out to NVE, which adopted a top-down technocratic implementation style. The mass roll-out was tightly controlled, overseen and pushed by policymakers (e.g. through penalties) and supported by industrial interests. The roll-out was successfully implemented, reaching 97% installation by January 2019.

Business environment: The 2013 deadline delay (from 2017 to 2019) gave DSOs an adequate planning horizon, and the mass roll-out proceeded generally smoothly, increasing cumulatively from 414,000 by December 2016, to 1.85 million by December 2017, and 2.9 million by December 2018. Implementation was also done efficiently, costing 10% below initial estimates (at 9 billion kroner). Although smart meters created benefits for industry players, these were limitedly passed on to consumers (Sareen and Rommetveit, 2019).

Technology: An additional innovation realized during the roll-out was Elhub, which aggregates and makes available all electricity consumption and production metrics for Norway, and continuously processes electricity market functions. This benefitted DSOs and suppliers by enabling a more integrated market for retail electricity in Norway and the wider Nordic region. Allowing seamless data flow on energy use to validated actors (including third-parties) eased the management of customer information, supplier switching, metering and billing.[4] Additionally, a stream of user-oriented applications and Internet-of-Things gadgets was becoming more widely available, supported by data access through Elhub.

Wider publics: There were protest groups such as 'Stopp smartmålene' (stop smart meters, established in 2018), campaigns like 'Nei til Smartmålere' with about 4,000 signatures[5], and Facebook groups with thousands of members against smart meters. But such expressions of public concern had limited traction on wider public debates, which remained relatively muted.

User environment: Smart meter installation in people's homes was mandatory and backed by penalties for blocking installation. Opting out was possible, but only for users with low consumption and a demonstrable disadvantage due to installation, or on the grounds of radiation concerns supported by a medical certificate. The opt-out rate was relatively low at 0.3%, plus 0.2% on medical grounds (NVE 2019; also see www.nymaler.no), which indicates that most people had limited concerns.

Tech-savvy users were offered a range of offerings, such as Swedish company Tibber's smartphone application, to analyse home energy use and enable energy saving. But real-life experiments found that such interventions only enabled substantial energy savings for unusually proactive users, while most participants did not sustain interest (Sareen and Rommetveit, 2019). Smart meters have thus generated relatively limited benefit for users.

4.4. Portugal

4.4.1. Business-led experimentation with smart meters (2006-2011))

Business environment: The Portuguese push for smart meters came from companies, particularly Energias de Portugal (EDP), a vertically integrated multinational energy company, and its subsidiary 'EDP Distribucao' (EDPD), which is the Distributed System Operator (DSO) for mainland Portugal. One reason for this push related to Portuguese power generation, which was an early leader in renewable electricity production (mostly wind, which grew from 58 MW in 1999 to 4,364 MW in 2011 and 5,313 MW of installed capacity in 2017, by which time its annual penetration was 24% (Bento and Fontes, 2015; Costa et al., 2019). The DSO was interested in smart meters as an enabler of a shift towards demand-response and smart grids, which it saw as a way of dealing with intermittent renewable electricity, which was expected to increase further while there were also plans to electrify more sectors. EDP thus perceived smart meters as part of a wider industrial strategy that included smart public lighting, demand side response (DSR), advanced digitalised electricity supply, and electric vehicles charging via the Mobi.e programme (Crispim et al., 2014). Another reason was that EDP saw the Portuguese market as a testing ground for new technologies and services that they hoped to subsequently implement in other operating markets like Brazil.

Technology: Testing and learning with smart meters began in 2007 with the prestige project *EDP Inovgrid* featuring 30,000 users in the town of Evora. The smart meters included in-home displays (IHD) to monitor consumption and (for solar prosumers) production. These so-called 'Energy boxes' communicated with Distribution Transformer Controllers (DTC), which improved grid intelligence for the DSO. Inovgrid became a leading European smart grid project, showing how a system can enable smooth system data flows for efficiency and grid control.

Policy environment: Policymakers and the Energy Services Regulatory Authority (ERSE) initially had limited engagement with smart meters. The 2012 cost-benefit analysis for smart electricity meters was positive (cost estimated at €99 and benefits at €202 per meter), but deemed inconclusive because of reliability doubts. Under the EU Directive, Portugal therefore had no obligation to complete a smart meter roll-out within eight years. Although Portuguese policymakers did not set targets, they did pass several primary laws to enable (but not mandate) smart metering ('Decreto-Lei n° 215-A/2012' and 'Decreto-Lei n° 231/2012').

Wider publics: Public debate hardly focused on smart meters, but instead focused on the financial crisis, economic recession and austerity politics, which deeply affected Portugal between 2008 and 2015. Average household primary energy consumption *decreased* by 13% from 2005 to 2013 (Nunes, 2018). Meanwhile, rising electricity prices exacerbated hardship and anger. The reputation and public trust in EDP was further damaged by scandals, such as 'revolving door' politics and favourable wind energy contracts (Silva and Pereira, 2019), leading to a low-trust sectoral context.

User environment: Consumers had limited engagement with smart meters. But electricity market liberalization in 2006 did give them more freedom to switch to new suppliers, which they increasingly used in subsequent years (Lopes et al., 2016).

4.4.2. Continued business pilots supported by policy incentives (2012-2015)

Business environment: EDPD continued to implement pilot projects as part of a wider smart grid strategy, including demand response programmes and direct load control (Lopes et al., 2016). EDPD expanded its Evora pilot to install 100,000 Energy boxes in six different locations, replicating the initial model of a plug-and-play solution ahead of an envisaged full roll-out. But before making long-term investments in a roll-out, EDPD wanted to ensure continued control of Portugal's distribution network. This was uncertain, however, because the long-term licenses were due to be tendered by Portuguese municipalities by 2020.

Technology: While the new Energy boxes included a Home Area Network (HAN) port, they no longer included an IHD. The reason was that evaluations of the Inovgrid project suggested that the majority of users did not consult the information on the IHD and did not practice demand-side management (Guerreiro et al., 2015).

Policy environment: Although policymakers did not articulate smart meter targets, ERSE introduced an incentive in 2012 that offered the DSO a 1.5% premium on the rate of return for 'smart' investments that enhanced distribution grid efficiency. The Portuguese case thus represents a "voluntary roll-out without a legislative mandate and with the primary goal of value maximization" (Pereira et al., 2018: 438). It is also characteristic of close cooperation between the regulator and the DSO, and consistent with the generally risk-averse policy style (Nunes, 2018).

[4] Cf. NVE's National Report 2017: https://www.ceer.eu/documents/104400/5988265/C17_NR_Norway-EN.pdf/ (accessed 05.03.2020).

[5] See https://www.underskrift.no/vis/5946.

Table 3
Summary of societal embedding processes in smart meter programs in four countries. Note: ICT = Information and Communication Technology. IHD = In-Home Display. DSO = Distribution System Operator. SMETS = Smart Metering Equipment Technical Specifications.

	Netherlands	UK	Norway	Portugal
Business implementation	By DSOs, who initially supported smart meters for narrow reasons (e.g. billing), but later also explored other opportunities, leading to proliferation of projects after 2017 with new products and smart-grid based energy services.	By energy suppliers, who became more hesitant because of technical problems and because cut-throat commercial competition changed their priorities.	By DSOs, who pushed for smart meters to deal with intermittent hydro-power and enhance supply-side efficiencies.	By DSOs, who pushed for smart meters to deal with intermittent wind power and as part of wider industrial strategy (energy services, exports).
Policymakers	Initially top-down planning, but more collaborative after protests.	Top-down planning (with early targets and specifications). Implementation problems created delays and led to (reluctant) adjustments.	Limited initial engagement, but then increasing move towards technocratic roll-out program.	Limited initial engagement, but gradual move towards stronger policies, e.g. financial incentive. No formal target.
Household adoption	Initially mandatory, but changed to voluntary after protests. Consumers can 'opt-out' (which 11% of population did). Some decline in consumer trust due to media reports about technical problems during mass roll-out.	Voluntary ('opt-in'). Some initial consumer interest, but stagnation after 2017 due to declining consumer trust because of technical problems, critical media debates, and negative reputations of energy suppliers.	Mandatory, but households can refuse in exceptional circumstances (which only 0.3% did). High confidence in government and technology (due to positive earlier ICT experiences).	Mandatory. Fairly passive acceptance, with cost of roll-out being absorbed by DSO and not placed on users. Moderate consumer confidence because scandals tarnished company reputation.
Wider publics	Strong initial opposition (about privacy concerns), which took 3-4 years to address. Subsequent roll-out was relatively quick.	Limited initial debate, but gradually increasing concerns about costs, technical problems, and privacy created social acceptance problems.	Limited public debate or opposition with costs recovered over many years.	Limited public debate or opposition.
Technical specifications	Societal protests led to various technical adjustments. IHD was optional extra.	Specifications articulated early on, including IHD. Subsequent mass roll-out encountered various problems with (e.g. SMETS1) that led to reluctant adjustments.	Public hearings and pilot projects led to adjustments (e.g. dropping IHD and remote steering) before mass roll-out.	Pilot projects led to technical adjustments (e.g. 'closed' energy box without IHD) with paid accessories made available.

Even when a 2015 cost-benefit analysis was clearly positive (estimated cost at €333 and benefits at €467), Portuguese policymakers eschewed formal commitment to a target, despite EU requirements.

Wider publics: Since there was no formal target for a smart meter roll-out, societal debate remained muted. Smart meters were not associated with high risks (Guerreiro et al., 2015). They were an innovation the DSO was rolling out without charging users equipment costs.

User environment: User engagement with smart meters was still limited (except for those involved in pilot projects). But high switching rates indicated active user participation in the liberalized retail electricity market (Lopes et al., 2016).

4.4.3. Mass roll-out despite no government target (2016-2019)

Business environment: Because of perceived benefits, the DSO engaged in mass roll-out despite the lack of a formal smart meter target. Although EDP had not yet secured the long-term grid licences, which were needed to continue the smart meter roll-out, it was relatively confident it would win these since the regulator was dependent on EDP's technical expertise to work out the terms for grid licencing. Starting slowly in 2016, the mass roll-out gathered pace in 2017, when 600,000 smart meters were installed, which represented 20%. By the end of 2018, deployment reached 1.25 million. In January 2019, EDPD called for greater regulatory clarity, because institutional uncertainties were affecting the roll-out.[6] ERSE responded (see below) and the roll-out continued at pace, reaching 2.5 million cumulative installations by September 2019. Reaching 80-100% deployment by 2022-23 thus seems feasible.

Not all went smoothly, however. An independent audit during 2017-18 levied a penalty against EDPD, because it had knowingly installed and charged for sub-standard equipment. EDPD had to reimburse affected consumers and replace the sub-quality meters. EDPD therefore secured a procurement deal for 800,000 well-tested smart meters with Siemens Portugal and Landis and Gyr (who had also supplied meters to Iberdrola in Spain).

The smart meter roll-out program and move towards smart grids was accompanied by organisational learning and an internal change program 'move2future', which aimed to transform EDPD's operational processes, systems and organisational structures (Nunes et al., 2017).

Technology: Innovators also aimed to align the Energy box with other promising technologies such as household-level battery storage. EDPD's latest version of the Energy box in 2020, which was advertised with the slogan 'A smart box for your smart home', aims for further high-tech compatibilities, such as with Internet-of-Things devices, to open up new commercial opportunities in relation to smart homes.[7]

Policy environment: Despite another positive cost-benefit analysis in 2018, the government continued to refrain from adopting a formal roll-out target. But in 2019, ERSE did establish a new regulatory framework for smart meters (including technical specifications), which aimed to provide greater clarity for business investment.

Future distribution grid concessions were not settled, however. A new Ministry of Environment and Energy Transition, formed in late 2018, challenged ERSE's proposal for grid licensing concessions, prolonging uncertainty for the DSO. These concessions were a topic of extended discussions, including parliamentary hearings in 2018 and 2019, which led municipalities to delay the floating of tenders for licenses.

User environment: Smart meter installations were free of charge for households, but mandatory. The DSO would decide about meter replacement, but had the obligation to inform consumers about smart meter use and smart grid services. The DSO retained smart meter ownership and partly recovered installation costs through payments from premium rate incentives. Smart meter users had the option of paying to access their consumption data (including real-time solar production for prosumers), but not many used this option. Since the

[6] See https://www.euractiv.com/section/energy/news/smart-meter-woes-hold-back-digitalisation-of-eu-power-sector/ (accessed 14.02.2020).

[7] See https://www.edp.pt/particulares/servicos/redy-en/how-it-works/ (accessed 14.02.2020).

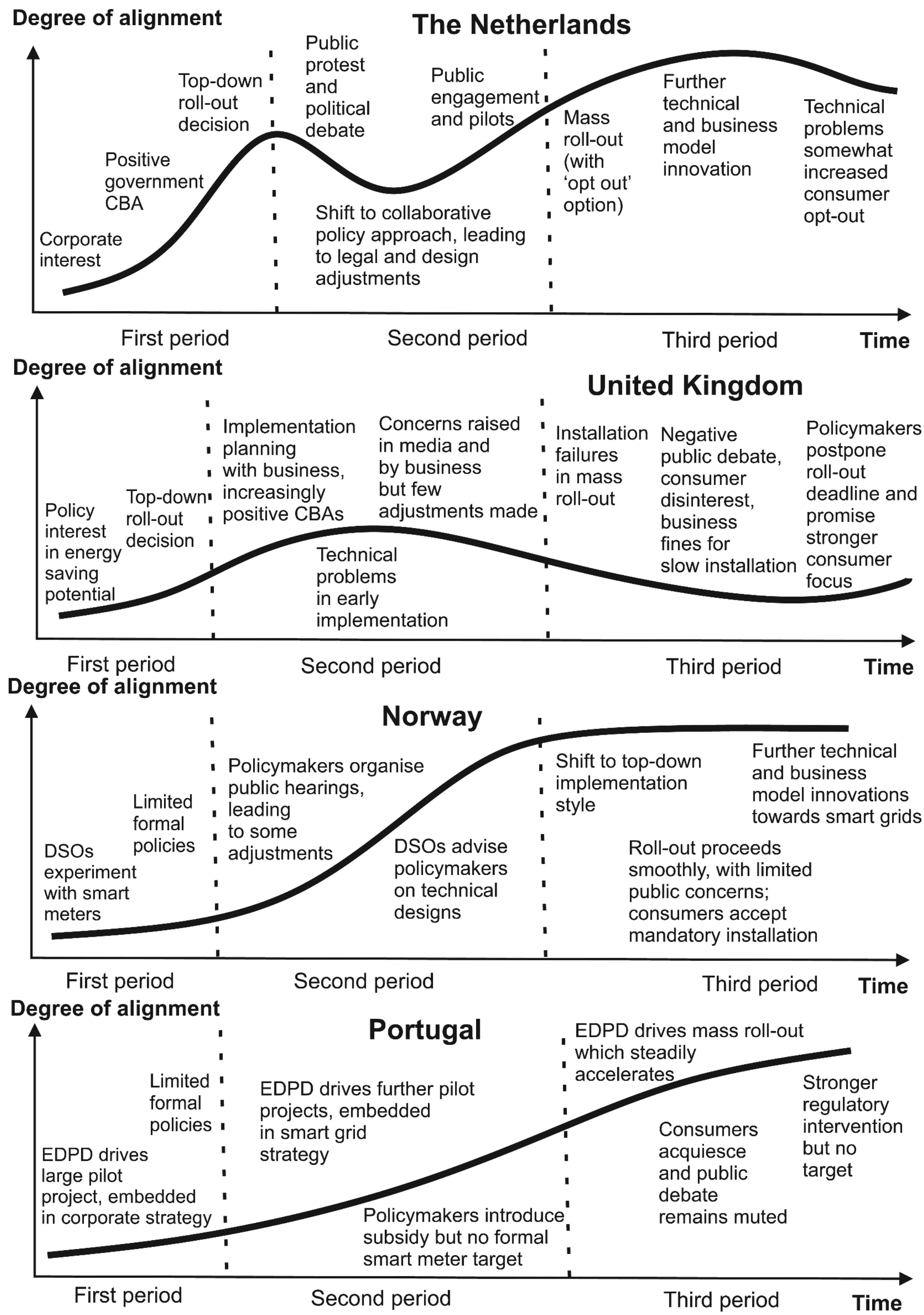

Fig. 7. Interpretive summary of temporal societal embedding patterns, with event sequences driving varying degrees of alignment (between smart meter technology and environments)

Energy box (without IHD) provided limited engagement opportunities, its benefits were unclear for many users. A 2019 survey found that only 35% of respondents knew what a smart meter is (Chawla et al., 2019).

Wider publics: Colloquially and in online forums complaints around erratic billing were ubiquitous, even after smart meter installation, and usually concerned EDPC (which likely reflects its dominant market position as a supplier).

5. Discussion and analysis

5.1. Different diffusion trajectories resulting from varied societal embedding processes

The four cases demonstrate that the accelerated diffusion of smart meters required alignment between technology and the four environments from the societal embedding framework. The Netherlands, Norway, and Portugal achieved this alignment (although in different ways), while the UK only partially succeeded, which explains recent stagnation in diffusion and delay in meeting targets. In all four cases, the initial push for smart meter diffusion came from government and/or business. But, as summarised in Table 3, the cases differ substantially in terms of how these actors subsequently engaged with consumers and wider publics and how technical specifications were adjusted (or not).

While the quantitative curves in Fig. 3 suggest that smart meter diffusion is a similar kind of process in the four countries with some variation in speed and depth of adoption, Table 3 implies that the qualitative diffusion *trajectories* varied considerably due to differences in societal embedding processes, e.g. in terms of which actors were the main drivers and what motivated them; the degree and content of public concerns; the way in which consumers were approached and how they responded; the roles and strategic considerations of companies; and how and when policymakers engaged with the implementation process.

Smart meter technologies also varied across the cases in terms of technical specifications and interpretations of their effects. Smart meters in Norway and Portugal were interpreted as part of wider envisaged transformations towards smart grids, demand-side response and broader industrial strategies. By contrast, actors in the Dutch and UK roll-outs initially assumed that smart meters would be transformative artefacts on their own (because information feedback was thought to trigger behaviour change and energy savings), which provided policymakers with a reason to push smart meter deployment.[8]

As a result of these societal embedding differences, the diffusion trajectories varied substantially between the four cases. The following metaphorical categorisations aim to capture salient differences in these trajectories, while Fig. 7 provides an interpretive schematic summary of temporal societal embedding patterns.

- The Dutch roll-out started with a push-approach but after societal protests, which lowered alignments, switched to a *curling* path, in which various 'brooming' activities (societal debate, technical adjustments, pilot projects) increased alignments that smoothened the ground for subsequent mass roll-out.
- The UK roll-out had characteristics of a halted *snow-shovelling machine*, with the government powering ahead (acting as a mechanical 'snow-shovelling machine') and pushing objections ('snow') aside, until accumulating social acceptance problems piled up to block and halt 'the machine', due to increasing misalignments.
- The Norwegian program can be characterized as a *ski-jump*, in which prolonged preparations ('descending down the ramp') through experiments, network building, and stakeholder consultations created alignment, which was followed by a high-speed 'jump' towards the roll-out target without much resistance.
- And the Portuguese program can be seen as a *snow-balling* pathway, in which the first pilot project was followed by others, which enabled learning and alignment and steadily increased company confidence and roll-out momentum.

5.2. Choices in the implementation of technology-forcing policies

The different diffusion trajectories and societal embedding patterns were shaped by the choices with regard to the two implementation dilemmas of technology-forcing policies: a) early or late formulation of targets and specifications, b) technocratic or emergent-adaptive implementation style.

[8] In retrospect, however, these transformative effects on energy consumption were wildly over-estimated and nowhere near the initial estimates.

- The Dutch case was characterized by an initially *technocratic style* and attempts by the government to legislate *early targets*, technical specifications, and mandatory installation. This top-down approach triggered civil society protests, which led to subsequent adjustments in technical and functional specifications, a change from mandatory to voluntary household adoption, and a delay in the targets. Most significantly, the implementation style changed from technocratic to emergent-adaptive, using pilot projects and public participation to articulate design specifics (while retaining some elements of top-down planning in the actual street-by-street roll-out). While these adjustments delayed the roll-out by a few years, the subsequent implementation was relatively rapid and generated further innovative projects in later stages to explore the potential of smart grid and energy services.
- The UK case was also characterized by a *technocratic style* and *early government formulation of targets*, technology specifications and a supplier-led roll-out model. Policymakers subsequently engaged primarily with businesses and corporate lobbies, creating a wide array of technical committees to discuss techno-economic issues, while paying little attention to consumers or social issues. In the second period (2010-2015) some of the early choices were found to be problematic: smart meters with SMETS1 standards had technical functionality problems, while the supplier-led roll-out prevented efficient street-by-street implementation (which is why all other European countries selected a DSO-led model). Public concerns about costs and privacy also negatively affected consumer attitudes. In response, UK policymakers and businesses adopted some elements of the *emergent-adaptive* implementation style such as consultation with civil society organizations and more pilot projects. But, contrary to the Netherlands, the resulting adjustments remained relatively superficial, e.g. new marketing campaigns, which represent one-directional information provision rather than bi-directional engagement. Ironically, one more substantial change (the switch to an 'opt-in' model for household adoption), which UK policymakers made when they perceived Dutch problems with the mandatory model, seriously underestimated the indifference and lack of trust of consumers, which, combined with ongoing public concerns, hampered diffusion after 2017.
- The Norwegian case was characterized by relatively *late targets* and an (initially) *emergent-adaptive implementation style*, in which DSOs advanced smart meters through early sequences of pilot projects that enabled social interaction and learning processes, which broadened and deepened understanding about possible benefits to include peak shaving, grid coordination, efficiency gains and consumer benefits. Policymakers became more involved in the second phase (2008-2016), when they interacted closely with businesses to articulate technological and organizational roll-out specifics. This included the formulation of formal targets and an accompanying shift towards more technocratic planning, in which policymakers centrally coordinated and enforced the roll-out, which proceeded smoothly and rapidly in the third phase without much user involvement.
- The Portuguese case was characterized by *no targets* (which we interpret as very late targets) and an *emergent-adaptive implementation style*, in which a major pilot project (EDP Inovgrid) and subsequent spin-offs enabled learning about the technology and consumer preferences. In the second phase (2012-2015), policymakers introduced a financial incentive to stimulate smart meter deployment, but refrained from adopting a formal target, despite a positive CBA in 2015. This was because the large incumbent DSO was already diffusing smart meters based on its wider smart grid and industrial strategy considerations, and because the regulator and DSO had cooperative relations. In the third phase (2015-2019), however, the DSO asked for greater regulatory clarity to accompany and underpin the relatively rapid and smooth roll-out.

Combining the two implementation dilemmas, Fig. 8 maps the initial

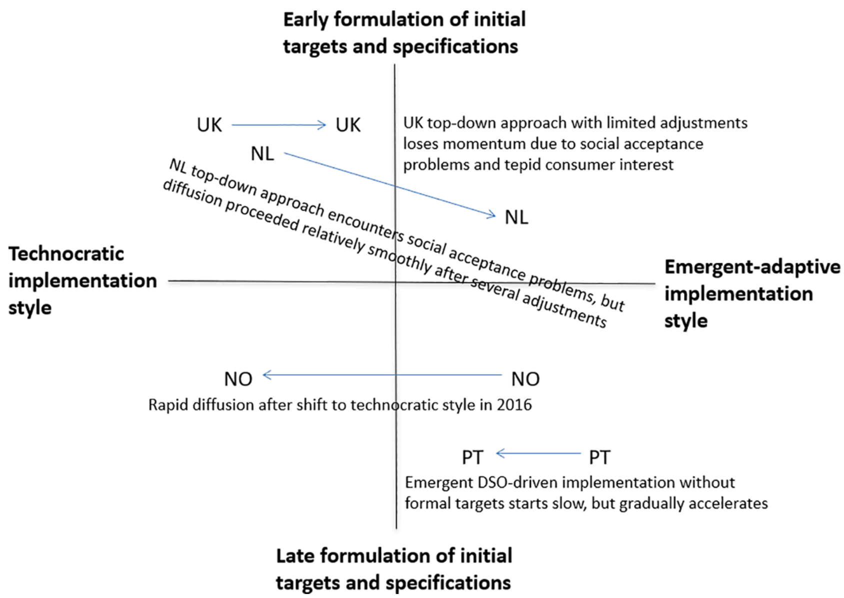

Fig. 8. Changing implementation styles during smart meter diffusion in the four cases

Table 4
Responses to drawbacks of early targets and technocratic implementation style in the Netherlands and UK smart meter roll-out

Potential drawbacks of early targets:	Netherlands	UK
-Unrealistic targets prove difficult to meet, leading to impression of failure. - Early specifications may turn out to be wrong.	- No. Adjustments created some delay, but prepared ground for later successful roll-out. - Partial. Initial specifications were adjusted in response to early protests, so were not wrong later on.	- Yes. Although diffusion is still progressing, the roll-out is perceived as failure. - Yes. Early choices (e.g. SMETS1, supplier-led roll-out, consumer 'opt-in' model) created problems later on.
Potential drawbacks of technocratic style:	**Netherlands**	**UK**
- Narrow stakeholder engagement and social acceptance problems; - Ignoring broader considerations; - Reluctance to learn and make adjustments.	- Initially yes. But early change to more participation improved social acceptance. - Initially yes. Therefore early consideration of wider issues. - No. Substantial willingness to learn and adjust.	- Yes. Subsequent consultation remained narrow and restrained by technocratic style. - Yes. Subsequent considerations remained narrow. - Yes. Adjustments remained superficial.

Table 5
Responses to drawbacks of late targets and emergent style in the Norwegian and Portuguese smart meter roll-out

Potential drawbacks of late targets:	Norway	Portugal
Creates uncertainty, delays commitments and slows diffusion.	Yes. Slow policy engagement and late targets created some uncertainty. This led to a shift towards a centralized planning style in the second and third phases.	No. Lack of targets did not delay commitments or diffusion (because smart meters were aligned with wider corporate strategies).
Potential drawbacks of emergent-adaptive style:	**Norway**	**Portugal**
- Fragmentation and limited information exchange among projects; - Slow initial diffusion due to time-consuming articulation process and delayed formal commitment.	- No. DSOs and industry association facilitated knowledge exchange and coordination. - Yes. Therefore shift towards centralized planning style to accelerate diffusion.	- No. Dominant DSO (EDPD) was involved in all projects.. - Partially. Pilot projects were large to start with. But there was a push for more regulatory clarity in the third phase.

choices in each country-case in a 2×2 matrix and the later adjustments in implementation styles that were made during the roll-out process: the Netherlands and Norway changed to different kinds of implementation styles, while the UK and Portugal made smaller adjustments that stayed within the initial style.[9]

This analysis suggests that there are (at least) two patterns for the successful implementation of technology-forcing policies:

1) Start with early targets and a technocratic style, but make adjustments (in technology specifications and perhaps implementation style) if there are substantial societal protests or technical problems (which the Netherlands did better than the UK).

2) Start with an emergent-adaptive style and formulate targets later (once technical and social stabilisation has occurred), which can then be enforced with less risk of substantial opposition (particularly Norway; Portugal to a lesser extent).

These two patterns point to an overarching tension for technology-forcing policies, which, should, on the one hand, provide a coordinated push to focus and drive technology deployment and, on the other hand, allow some degree of openness and flexibility to enable sufficient learning, stakeholder engagement, and mutual adjustment. The two patterns each start on one side of this overarching challenge and then gradually accommodate elements from the other side.

5.3. *Style changes to mitigate drawbacks of initial choices*

With regard to this overarching challenge, each country experienced some of the potential drawbacks of initial choices specified in Table 1, which led to changes in their implementation style. The Netherlands and the UK both experienced some of the drawbacks of early targets/specifications and a technocratic style, but responded differently (see

[9] The Dutch case also involved a change in the timing of initial targets, as early attempts at legislation were rejected by the Senate, leading to later formulation of targets.

Table 4). Dutch policymakers were willing to make substantial adjustments to mitigate the drawbacks, which resonates with the country's political consensus and compromise culture.

The UK also experienced drawbacks of initial choices, but policymakers made only limited adjustments to address the problems (Table 4). This resonates with the UK's centralized political culture and top-down leadership style, observed by King (2015: 283): "The government in the UK is still meant to govern – full stop. It is not meant to, and does not, share power with others. (…) The government of the day is expected to take the initiative. The government of the day acts. Others react. (…) Reforms (…) are not negotiated painstakingly with stakeholders. They are handed down from above by governments". The UK's continued adherence to a top-down planning style was a major reason for the stagnated diffusion, because it insufficiently accommodated stakeholder engagement and the intrinsic uncertainties of radical innovations.

Norway and Portugal differentially experienced some of the drawbacks of *late targets/specification* and *emergent-adaptive style*, leading to different responses (Table 5). In response to regulatory uncertainties and the slow speed of emergent learning and interaction processes, Norwegian policymakers shifted towards a more centralized planning style in later periods. Norwegian consumers and stakeholders accepted this style change, because they generally trust their government and because positive experiences with earlier ICT roll-out programs had reduced people's concerns about privacy (Ballo, 2015).

Potential drawbacks did not strongly manifest themselves in Portugal (Table 5), mostly for case-specific reasons such as the presence of a DSO that was committed to smart meters for broader strategic reasons, which is why implementation style changes remained limited. The Portuguese government's reluctance to adopt a formal target also relates to a risk-averse political culture and tight networks between policymakers and EPD (Nunes, 2018).

This analysis shows that implementation styles in all four countries were dynamic in the sense that policymakers made some (smaller or larger) changes to address the overarching tension between flexibility and coordinated push. Countries starting with a technocratic push (Netherlands, UK) later introduced more flexibility, while countries starting with an emergent-adaptive approach (Norway, Portugal) later introduced more top-down coordination. This confirms our proposition that both styles are extremes and that countries may combine elements from both over time. While Portugal and the UK both made limited adjustments to their initial styles, this was relatively unproblematic in Portugal (because the specified drawbacks associated with its style did not materialize prominently), but highly problematic in the UK (because all specified drawbacks of technocracy materialized and were insufficiently addressed), which explains its stagnated diffusion.

6. Conclusions

The article has shown that technology-forcing policies can accelerate the diffusion of new technologies into markets and society, and that implementation of these policies involves choices with regard to two dilemmas: early or late formulation of initial targets, and technocratic or emergent-adaptive implementation styles. These dilemmas are particularly pertinent for radical innovations whose diffusion involves not only policymakers and firms, but also consumers and civil society organizations. We conceptualised these dilemmas using insights from the societal embedding of technology framework and from four different policy steering theories. And we empirically investigated the dilemmas with a comparative analysis of smart meter diffusion in four European countries, which showed that policy choices substantially shaped the diffusion trajectories.

Although there is no definitively correct way to navigate the dilemmas, our analysis identified two patterns for successful implementation of technology-forcing policies. The first pattern is to start with early targets and a technocratic style, but make sufficient adjustments if there are substantial protests or technical problems. This pattern occurred in the Dutch case, where policymakers made substantial technical and policy adjustments when they encountered. societal protest and acceptance problems. By contrast, UK policymakers continued to adhere to top-down technocratic implementation and did not make sufficient adjustments when the roll-out encountered technical and social acceptance problems, which derailed smart meter diffusion.

The second pattern is to start with an emergent-adaptive style and formulate and enforce targets later, once technical and social stabilisation has occurred. This pattern occurred in the Norwegian case, where a prolonged period of learning and stakeholder interactions, which generated technical and social stabilisation, was followed by a shift to a top-down planning style that drove very rapid smart meter deployment. The Portuguese smart meter roll-out also started with bottom-up initiatives, but despite stabilisation policymakers did not formulate formal targets in later phases, although there was some shift towards more centralized coordination.

Both technocratic and emergent-adaptive policy styles can thus accelerate technological diffusion. In fact, our analysis showed that all cases had elements of both styles. To navigate the overarching tension between flexibility and a coordinated push, countries that started with one style subsequently introduced elements from the other style, and vice versa.

Our findings contribute not only to debates about technology-forcing policies, but also bear relevance for wider debates about transformative innovation policy and mission-oriented innovation policy, which both signal increasing interest in grand challenges, radical innovation, and a stronger role for policymakers. But, in our view, advocates of the former (e.g. Schot and Steinmueller, 2018) go too far in emphasising bottom-up experimentation and rejecting top-down planning, while advocates of the latter (e.g. Mazzucato, 2018) place too much emphasis on state-guided R&D programs and firm-led innovation (visible in their admiration for the Apollo or Manhattan programs, which included neither citizens nor civil society actors). Since neither approach sufficiently engages with diffusion, our research findings offer useful complements, including the following general principles: 1) while experimentation and learning-by-doing are important in early phases, centralized planning and technology-forcing policies may cost-effectively drive diffusion in later phases; 2) while firms and policymakers are important actors, diffusion also requires involvement of consumers and wider publics, not just in the up-front formulation of missions, but also throughout the implementation process; 3) embedding technologies in wider transformation programs is likely to be a more effective strategy than pushing technologies as stand-alone transformative devices.

Based on our case analysis, we also propose several instrumental suggestions for the implementation of technology-forcing policies aimed at accelerating diffusion[10]:

- If companies are interested in the technology for strategic reasons (e.g. because they perceive it as part of wider transformations), start with an emergent-adaptive approach that stimulates learning, interaction and adjustments (PT, NO). If progress is too slow, shift to a technocratic style, including demanding deployment targets, once learning processes have sufficiently stabilized the technical design (NO).
- If companies show moderate interest, start with a technocratic approach and set demanding deployment targets to push them (UK, NL), but refrain from detailing technical specifications to prevent early lock-in in sub-optimal designs (which dogged the UK case).
- If implementation encounters substantial societal protest, make adjustments in roll-out specifications or implementation style that

[10] We want to thank one of the reviewers for stimulating us to discuss more instrumental policy suggestions.

sufficiently alleviate the concerns (NL). Otherwise, diffusion may grind to a halt (UK).
- Always allow for sufficient technological learning before mass roll-out, either by making adjustments (NL) or by delaying the formulation of targets and specifications (PT, NO). Otherwise, unforeseen problems may occur that can hamper mass diffusion (UK).

One weakness of our comparative and longitudinal research design is that we could only briefly discuss the various actors in each period and country. Because of inevitable trade-offs between breadth and depth, we were unable to more deeply investigate interpretations, motives, and (strategic) considerations of different actors or their coalitions. Another weakness is that we only limitedly addressed structural contexts for policy decisions and societal embedding processes. Although we touched on policy cultures and public trust in government institutions and energy companies, space constraints precluded us from delving more deeply into political, cultural and economic structures (including energy system structures).

Nevertheless, we hope that our article has opened up new insights and questions with regard to accelerated diffusion and technology-forcing policies, which are rising again on policy agendas related to sustainability and low-carbon transitions, where the pace of change is too slow at present. The societal embedding framework is relevant for technology-forcing in open-ended diffusion processes, but addressing multiple actors and factors increases policy complexity. One interesting issue for future research is thus whether policymakers require new skills and competencies in order to analyse and manage this complexity.

Another interesting issue is to investigate technology-forcing policies for innovations that are more radical and comprehensive than smart meters, which deviated substantially from existing capabilities of energy companies but were relatively inexpensive, simple in design, and invisible from a consumer perspective (and were framed as technical grid upgrades in Norway). For more radical and comprehensive innovations, we would not only expect involvement of more actors and thus higher policy complexity, but also greater implementation challenges of technology-forcing policies. The 2006 UK zero-carbon homes target, which stipulated that all new homes should be carbon neutral by 2016, may be an interesting case in this respect, because persistent opposition from housebuilders and lukewarm interest from home-buyers (for whom energy-efficiency is relatively unimportant compared to other home-purchase criteria) led to the dismantling of the technology-forcing policy in 2015 (O'Neill and Gibbs, 2020).[11]

Lastly, having established that the technocratic implementation style can (sometimes) accelerate technology diffusion, it would be interesting to further investigate the conditions under which this style works (or not). Such research would thus further open up the widespread assumption in innovation studies that emergent-adaptive policy styles are necessarily better or preferable.

Credit author statement

Frank Geels: Conceptualization; Formal analysis; Methodology; Supervision; Writing – original draft; Writing – review and editing. **Siddharth Sareen**: Investigation; Writing – review and editing. **Andrew Hook**: Investigation; Writing – review and editing. **Benjamin Sovacool**: Data curation; Funding acquisition; Investigation; Project administration; Supervision; Visualization; Writing – review and editing.

[11] House-builders balked at zero-carbon homes, because the concept involves many interdependent innovations (e.g. highly-insulated building fabric, insulated glazing, air tightness solutions, heat recovery for ventilation, and low-carbon heat sources such as solar thermal or heat pumps) and deviates substantially from the existing standardised design and production templates.

Declaration of Competing Interest

The authors confirm that they have no conflict of interest.

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